

CONCEPTUALIZATION AND QUANTITATIVE ASSESSMENT OF RISK ASSOCIATED WITH EXPLOSIVES

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Abstract: *The management of explosion risk at explosives warehouses allows ensuring the necessary premises for the development, in objective and specific conditions, of the necessary documents for these types of technical infrastructures, right from their design phase and the quantification of the degree of impact on the sites analyzed as well as the areas that are located in their vicinity. In the case of the quantitative evaluation of the explosion risk generated following the detonation of explosive materials, the estimation of the manifestation of hazards identified through the associated risk factors should be carried out based on scientific calculation algorithms and established grapho-analytical models. The paper summarizes part of the results obtained regarding the development of a methodological approach and specific application tools that allow the assessment of the major accident risks generated by explosive materials, the identification, formalization and structuring of the applicable safety requirements to reduce or eliminate the risks in explosive material storage sites.*

Keywords: *major accident, explosives, risk assessment, overpressure, structural response, individual and group risk*

1. Introduction

On July 10, 1976, the city of Seveso, Italy, became the survivor of a major industrial accident that occurred within a chemical plant. This accident occurred when a disk from a chemical reactor ruptured, resulting in the release of a dense and white cloud, which contained a small "storage" of the highly toxic substance known as 2,3,7,8-tetrachlorodibenzop-dioxin (TCDD) [1].

This led to drafting the first Seveso Directive aimed both at prevention of major accidents occurrence and to protection of workers /citizens [2]. Following other major industrial accidents around the world - in Bhopal (India), Mexico City (Mexico), Toulouse (France) and Enschede (Netherlands) - the original version of SEVESO was reformulated in the Council by the Directive called Seveso II [3]. One of the main objectives in this "iteration" of the directive was to address the hazard that arises when hazardous facilities/sites and neighboring targets are located in close proximity to each other, the land use planning issues when new facilities/sites are authorized and when urban development takes place around existing facilities [4]. In 2012, a third iteration of the legislation was passed, entitled Directive 2012/18/EU of the European Union Parliament (Seveso III), introducing two different classes of sites and revising the list of hazardous substances [5].

At the present time, it is increasingly admitted and recognized that the vast majority of industrial accidents have as their fundamental cause the faulty way in which management is carried out at the level of economic operators [6].

Explosives warehouses can be considered as critical infrastructures, especially taking into account the criterion of extent, the amplitude of the effects of an explosion produced in a warehouse, but also the possible severity on economic activity, the public and the environment [7, 8]. It is recommended, more and more, that the processes of identification, evaluation and control of risks are carried out proactively rather than reactively [9].

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The implementation of technical means of protection can increase costs, if these means are implemented after the design of an explosives storage site is completed or after its construction [10, 11]. In general, changes made at the design stage are less expensive and more effective than those made later, which fully justifies starting the risk analysis and assessment process from this stage [12, 13].

Risk, understood as a statistical value, is usually quantified mathematically as the product of probability and consequences. However, the definition of risk (or conversely, safety) is not universal, unambiguous and objective [14]. Therefore, a comprehensive risk-based safety assessment must consider the following types of risks at the same time [15]:

- **Individual risk** - risk to the exposed person, which focuses mainly on his own hazards, regardless of the number of people who are also exposed;
- **Real collective risk** (also known as **group risk**) - the total risk of the group of exposed persons, which represents the entire hazard of the activity, in which society is primarily interested;
- **Perceived collective risk** - the actual collective risk increased by a factor, depending on how the parties responsible for the hazardous activity and who are interested in limiting the hazard in such a way that the public will not oppose this activity and which predicts the proportional response of society to accidents with high consequences due to the specific field of hazardous activity.

The methodologies for analysis, evaluation and classification of major accident (explosion) hazards, in the case of explosives warehouses, allow the quantification of the possible effects on the neighborhood and on human health, including the delimitation of emergency planning areas [16].

A viable solution to the problem of major risks specific to the technical infrastructures intended for the storage of explosive materials must help to carry out a quick analysis of the site, to impose conditions prior to the construction of the objective from its design phase.

This paper summarizes some of the results obtained regarding the definition of a methodological approach and specific application tools that allow the assessment of the risks of a major accident generated by explosive materials, the identification, formalization and structuring of the safety requirements applicable to reduce or eliminating risks in explosives storage sites.

2. Material and method

2.1. Conceptualization of the notion of risk specific to industrial sites where operations with explosive materials are carried out

The methodology of quantitative risk assessment, addressed in this paper, is based on the concept of risk developed since 1662 by the French mathematician Blaise Pascal, who argued that: „*Our fear of harm should be proportional, not only with the extent of the affect, but also with the probability of the occurrence of the event that generated it*”.

In the occupational sense, the risk can be expressed mathematically by the following basic relationship:

$$R = P \times G, \quad (1)$$

where: R - professional risk (of occupational injury and/or illness);

P - probability of occurrence of the unwanted event;

G - severity of the maximum foreseeable consequence.

If the occurrence of an „explosion” type event (generated during specific operations with explosive materials carried out in a year) is expressed in terms of probability, and the undesirable consequences in terms of probability of death or injury by producing major/minor injuries ($P_{dl}^{M,m}$) (taking into account the presence of the human operator), then relation (1), in the case of individual risk, becomes:

$$R_{individual} = P_{dl}^{M,m} = P_{explosion} \times P_{dl}^{M,m/explosion} \times E_{personal}, \quad (2)$$

where: $P_{dl}^{M,m}$ - annual probability of death or injury from major / minor injuries;

$P_{explosion}$ - the annual probability of an explosion-type event occurring on a site intended for specific operations with explosive materials;

$P_{dl}^{M,m/explosion}$ - probability of death or major/minor injury following an explosion-type event, given the human operator's exposure to the event;

$E_{personal}$ - personal human exposure to the occurrence of an explosion-type event on a site intended for specific operations with explosive materials „hours/year”.

In the case of collective risk, applied to a group of people exposed to an explosion-type event, relation (2) becomes:

$$R_{group} = \sum P_{d,l^{M,m}} = \sum (P_{d,l^{M,m}} = P_{explosion} \times P_{d,l^{M,m}/expl} \times E_{personal}) \quad (3)$$

where:

R_{group} - collective risk when an explosion-type event occurs on a site intended for specific operations with explosive materials.

Following the explanation of the term $P_{d,l^{M,m}/explosion}$ (taking into account the theoretical aspects in the Note), relation (2), becomes:

$$P_{d,l^{M,m}/explosion} = \left[\begin{aligned} &P_{\frac{d,l^{M,m_1}}{explosion}} + \left(1 - P_{\frac{d,l^{M,m_1}}{explosion}}\right) \left(P_{\frac{d,l^{M,m_2}}{explosion}}\right) \\ &+ \left(1 - P_{\frac{d,l^{M,m_1}}{explosion}}\right) \frac{\left(1 - P_{\frac{d,l^{M,m_2}}{explosion}}\right) \left(P_{\frac{d,l^{M,m_3}}{explosion}}\right) + \left(1 - P_{\frac{d,l^{M,m_1}}{explosion}}\right)}{\left(1 - P_{\frac{d,l^{M,m_2}}{explosion}}\right) \left(1 - P_{\frac{d,l^{M,m_3}}{explosion}}\right) \left(P_{\frac{d,l^{M,m_4}}{explosion}}\right)} \end{aligned} \right] \quad (2')$$

where: $P_{d,l^{M,m_1}/explosion}$ - risk of death or injury from major/minor injury caused by overpressure and impulse;

$P_{d,l^{M,m_2}/explosion}$ - risk of death from broken windows and destruction of buildings;

$P_{d,l^{M,m_3}/explosion}$ - risk of death or injury through the production of major/minor injuries caused by the projection of fragments resulting from detonation;

$P_{d,l^{M,m_4}/explosion}$ - risk of death or injury through the production of major/minor injuries caused by the thermal effect.

Note: Applying the mathematical rule of adding 4 independent events (X_1, X_2, X_3, X_4) graphically visualized in figure 1, taking into account the occurrence probabilities of each one, it is obtained:

$$\begin{aligned} P(X_1 \cup X_2 \cup X_3 \cup X_4) &= P(X_1) + P(X_1^c \cap X_2) + P(X_1^c \cap X_2^c \cap X_3) + P(X_1^c \cap X_2^c \cap X_3^c \cap X_4) = P(X_1) + \\ &P(X_1^c)P(X_2) + P(X_1^c)P(X_2^c)P(X_3) + P(X_1^c)P(X_2^c)P(X_3^c)P(X_4) = P(X_1) + (1 - P(X_1))P(X_2) + (1 - P(X_1)) \\ &(1 - P(X_2))P(X_3) + (1 - P(X_1))(1 - P(X_2))(1 - P(X_3))P(X_4) \end{aligned}$$

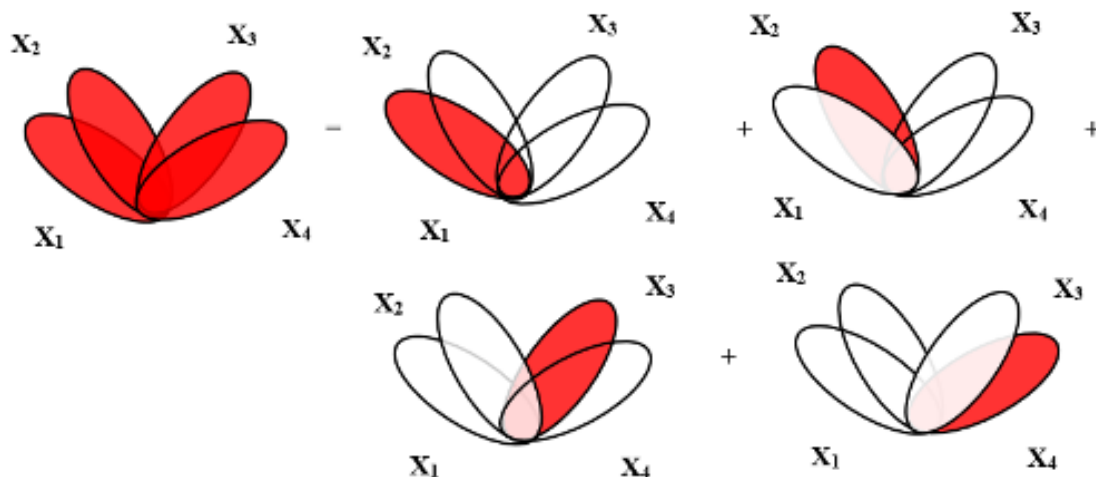


Figure 1. The grapho-analytical model for applying the mathematical rule of adding 4 independent events, taking into account the probabilities of each of them occurring

In the field of risk analyzes associated with explosion-type events caused by specific operations with explosive materials, the logarithmic scale is usually used to estimate the result indicator (see tables 1 and 2), because: the range of values specific to the area of interest for carrying out the risk estimation can include several orders of magnitude; lends itself very well to quantitative risk assessment; the principle of proportional logic is ensured, according to which multiplying the risk by a constant value leads to a constant separation (variation) of it.

Table 1. Numerical scales used in quantitative risk assessment

Numerical scale type					
Roman	Hindi / Arabic		Logaritmik, version		
	Percentage		Decimal	Scientific	Engineering
	0	0 %	0, 0000000001	10^{-10}	1E-10
	0,5	50 %	0, 000000001	10^{-9}	1E-09
I	1	100 %	0, 00000001	10^{-8}	1E-08
II	2		0, 0000001	10^{-7}	1E-07
III	3		0, 000001	10^{-6}	1E-06
IV	4		0, 00001	10^{-5}	1E-05
V	5		0, 0001	10^{-4}	1E-04
VI	6		0, 001	10^{-3}	1E-03
VII	7		0, 01	10^{-2}	1E-02
VIII	8		0, 1	10^{-1}	1E-01
IX	9		1	10^0	1E+00
X	10		10	10^1	1E+01
			100	10^2	1E+02
			1.000	10^3	1E+03
			10.000	10^4	1E+04

Table 2. Numerical scale configured based on logarithmic scale

	Fraction	Scientific version	Engineering version
Fraction	2/3	$6,67 \times 10^{-1}$	6,67E-01
	1/10	$1,00 \times 10^{-1}$	1,00E-01
Small fraction	1/3.000	$3,33 \times 10^{-4}$	3,33E-04
	7/100.000	$7,00 \times 10^{-5}$	7,00E-05
Extremely small fraction	1/100.000.000	$1,00 \times 10^{-8}$	1,00E-08
	5/10.000.000.000	$5,00 \times 10^{-10}$	5,00E-10

2.2. Quantitative evaluation of the explosion risk generated following specific operations with explosive materials

Considering the previously mentioned technical aspects, in table 3 we highlight the risk assessment matrix that is based on the concept of compliance with the principle of logical proportionality, respectively.

Risk assessment is a sequential process that involves both the quantitative risk estimation based on available data and information (accident history and statistics, test and trial results, technical-scientific information, safety data sheets, technical product specifications, experience and the technical expertise in the field of the experts), as well as the qualitative evaluation regarding the risk assessment taking into account the subjective aspects and the perception of the way of manifestation and generation of specific effects, according to table 4.

Table 3. Risk assessment matrix

Likelihood class	Severity class				
	Catastrophic	Critical	Average	Negligible	p
Frequent	M	M	S	Me	10^0 10^{-1}
Probable	M	M	S	Me	10^{-2}
Ocasional	M	S	Me	Mi	10^{-3}
Rare	S	Me	Me	Mi	10^{-4} 10^{-5} 10^{-6}
Unlikely	Me	Me	Me	Mi	10^{-7} 10^{-8} 10^{-9}

Legend: M-high risk; S-significant risk; Me-average risk; Mi-low risk

Table 4. Risk assessment matrix: direction of reducing P and G

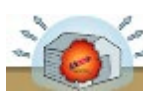
Risk assessment	Qualitative	Severity class, G	Likelihood class, P					
				Frequent	Probable	Ocasional	Rare	Unlikely
			Catastrophic	M	M	M	M	Me
			Critical	M	M	M	Me	Mi
			Average	M	Me	Me	Mi	Mi
	Negligible	Me	Mi	Mi	Mi	Mi		
	Quantitative	1 x 10 ⁻⁶ – estimation of annual probability of death value of the, P _{deces}						
Legend: M-high risk; Me-average risk; Mi-low risk			Direction of reducing P and G					

The exposure of people is a measure of the probability ($0 < P < 1$) that they will be present at the time of the explosion-type event, being expressed in the number of hours per year (in the case of the exposure of a single person), and in the case of several exposed persons, the number of hours in a year is multiplied by the number of these persons.

Table 5 shows the main mechanisms of damage through death or injuries (major or minor), as well as through material destruction, following the occurrence of an explosion-type event when carrying out specific operations with explosive materials, which can be grouped as follows:

- *Overpressure and impulse* (overpressure from the shock wave front);
- *Structural response* (destruction of buildings and shattering of windows with projecting resulting fragments);
- *Debris* (fragments resulting from the detonation of explosive materials, originating from: explosive products – primary fragments; construction materials of spaces intended for operations with explosive materials – secondary fragments; pieces of rock from formed craters – auxiliary debris);
- *Thermal radiation* (specific to explosives included in the division HD 1.3 - explosives that cause massive fires).

Table 5. Highlighting the effects of the main damage mechanisms generated by the detonation of explosive materials

	Inside the space intended for operations with explosives	Between the explosives area and the office building	Next to the office building	Inside the office building
Pressure and impulse				
Destruction of windows and building				
Debris				
Thermal radiation				

The effects and consequences of each previously mentioned impact mechanism occur successively, respectively, the danger that generates an explosion-type event inside the space intended for operations with explosive materials affects the structure of its building which is located at a certain distance from the building of offices, potentially affecting its structure, and consequently the human component present inside it.

2.3. Criteria for the acceptability of the explosion risk generated during specific operations with explosive materials

In 1999, the DoD (Department of Defense in U.S.A) sponsored the development of risk criteria for use in the risk-based management of explosives. Initially, these criteria were to be used based on objective scientific evidence for decisions related to the disposition of explosives facilities within dedicated industrial sites. To support the development of these criteria, various data and information on risk acceptability have been collected from a wide variety of credible sources made available by authorities with powers and responsibilities in this regard.

Likewise, the answer to the question: „*How safe is safe enough?*” is an essential ingredient in establishing any risk criterion. Although the question is fundamental to achieving the practical goal of establishing risk criteria, it is also a somewhat philosophical question, in the sense that it requires and challenges decision-makers to make subjective interpretations of the legal aspects that establish the applicable limit values, as well as of value limits specific to protected areas, also taking into account the practical experience in the field of solving the risk problem. Thus, a set of four risk criteria was developed for the management of explosion risk specific to operations with explosive materials (table 6), respectively:

Table 6. Risk limitation/reduction criteria depending on the human dimension and professional or civil affiliation of the exposure

Risk for:	Risk limitation/reduction criteria
Any worker (in the case of a single worker) (P_{fannual})	Limiting the maximum risk to the value of 1×10^{-4}
All workers (in the case of a group of workers) (E_{fannual})	Risk reduction to 1×10^{-3} Acceptance of exceeding the value of 1×10^{-2} only for significant national needs
Any person (in the case of a single person) (P_{fannual})	Limiting the maximum risk to the value of 1×10^{-6}
Public (in the case of a group of people) (E_{fannual})	Risk reduction to 1×10^{-5} Acceptance of exceeding the value of 1×10^{-3} only for significant national needs

Establishing the main scenarios for the disposition of explosive structures (PES) and exposure (ES) at the level of industrial sites intended for specific operations with explosive materials

The risk analysis must be carried out in a way that recognizes the mechanism of compliance with the mathematical legitimacy of „adding” the risk values taking into account its nature. In this sense, the risk-based disposition of explosive structures (PES) and exposure structures (ES) within an industrial site intended for carrying out specific operations with explosive materials, is done by ensuring that all PES-type structures that expose a structure of ES type at a significant „*individual risk – $R_{\text{individual}}$* ” are taken into account in the analysis and by evaluating the „*group risk*”. Thus, the „*group*” for a PES is considered to be made up of all persons exposed to a significant risk from that PES, and the „*group risk – R_{group}* ” is the total risk for all individuals in the group. In order to determine the „*group risk*”, the „*individual risks*” for all individuals in the group must be determined first (in addition to these individual risks, the specific risks of people from other PESs will also be taken into account). „*Group risk*” is determined by adding up all „*individual risks*”.

Conducting risk-based siting is a complex process, and adding a single PES or ES to an area with multiple such structures can cause a multiplicative effect on the overall risk profile, requiring determination of the effect the new PES or ES has on the general situation existing at a given time.

For the complete definition of event scenarios within the framework of risk analyses, which are subject to the involvement of explosive materials, specific data and relevant information necessary for the full characterization of explosive structures (PES) and exposure structures (ES) must be used, respectively: size, shape, type and construction category, orientation, type of explosive, classification in the hazard class and compatibility group of the explosive, the net amount of explosive stored/used, the type of activity carried out at the level of the exposed structure, the number of people present and the annual exposure (in hours) at the level of the exposure structure.

Taking into account the above, below we highlight the main scenarios for the disposition of explosion structures (PES) and exposure structures (ES), at the level of an industrial site intended for specific operations with explosive materials, respectively:

I. Scenario no. 1 of the arrangement of two distinct structures (ES and PES)

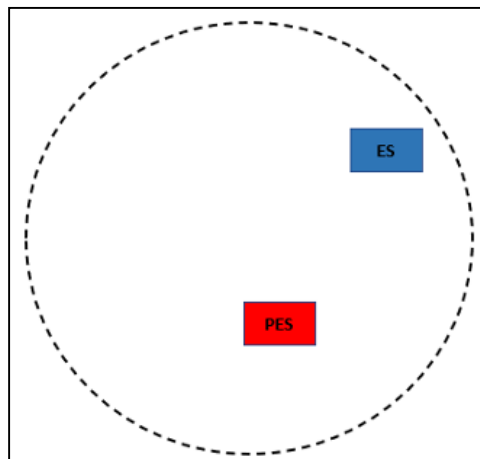


Figure 2. The risk-based disposition of two distinct structures of type PES and ES

In order to safely place an ES-type structure in the case shown in figure 2, the following work process algorithm must be followed:

a₁. If the ES is procedurally dependent on the PES, then the following procedural steps are followed:

Step 1a₁: The individual risk ($R_{\text{individual}}$) generated by the PES is calculated for each person in the ES;

Step 2a₁: If the maximum $R_{\text{individual}}$ calculated in step 1a₁ does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-4} , then the risk is acceptable;

Step 3a₁: The summation of the values related to all the individual risks calculated in step 1a₁ to determine the group risk (R_{grup});

Step 4a₁: If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-3} , then the risk is acceptable.

b₁. If the ES is procedurally independent from the PES, then the following procedural steps are followed:

Step 1b₁: The individual risk ($R_{\text{individual}}$) generated by the PES is calculated for each person in the ES;

Step 2b₁: If the maximum $R_{\text{individual}}$ calculated in step 1b₁ does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-6} , then the risk is acceptable;

Step 3b₁: The summation of the values related to all the individual risks calculated in step 1b₁ to determine the group risk (R_{grup});

Step 4b₁: If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-5} , then the risk is acceptable.

For the safe placement of a PES type structure, the same work algorithm is applied, respecting the process reasoning.

II. Scenario no. 2 of arranging several exposure structures in relation to a single explosion structure (ES 1, ES 2, ES 3 and PES)

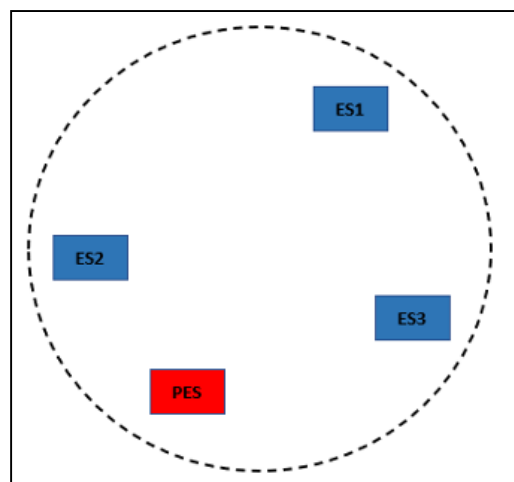


Figure 3. Risk-based layout of four distinct structures (ES1, ES2, ES3 and PES)

In order to safely place several ES-type structures in the case shown in figure 3, the following work process algorithm must be followed:

a_{II}. If the three ES structures are procedurally dependent on the PES, then the following procedural steps are followed:

Step 1a_{II}: Calculate the individual risks ($R^{1,2,3}_{\text{individual}}$) generated by PES for each person in ES1, ES2 and ES3;

Step 2a_{II}: If the maximum $R^{1,2,3}_{\text{individual}}$ calculated in step 1a does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-4} , then the risk is acceptable;

Step 3a_{II}: The summation of the values related to all the individual risks calculated in step 1a_{II} to determine the group risk (R_{grup});

Step 4a_{II}: If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-3} , then the risk is acceptable.

b_{II}. If the three ES structures are procedurally independent of the PES, then the following procedural steps are followed:

Step 1b_{II}: Calculate the individual risk ($R^{1,2,3}_{\text{individual}}$) generated by PES for each person in ES1, ES2 and ES3;

Step 2b_{II}: If the maximum $R_{\text{individual}}$ calculated in step 1b_{II} does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-6} , then the risk is acceptable;

Step 3b_{II}: The summation of the values related to all the individual risks calculated in step 1b_{II} to determine the group risk (R_{grup});

Step 4b_{II}: If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-5} , then the risk is acceptable.

For the safe placement of a PES type structure, the same work algorithm is applied, respecting the process reasoning.

III. Scenario no. 3 of the arrangement of several explosive structures in relation to a single exposure structure (PES1, PES2 and ES)

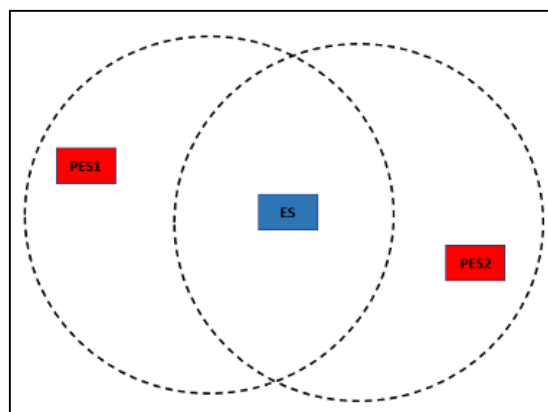


Figure 4. Risk-based layout of the three distinct structures (PES1, PES2 and ES)

In order to safely place an ES-type structure in the case shown in figure 4, each PES will be evaluated individually following the following work process algorithm:

a_{III}¹. If the ES is procedurally dependent on PES1, then the following procedural steps are followed:
PES1

Step 1a_{III}¹: The individual risks ($R_{\text{individual}}^{1,2}$) generated by PES1 and PES2 for each person in the ES are calculated;

Step 2a_{III}¹: If the maximum $R_{\text{individual}}^{1,2}$ calculated in step 1a_{III}¹ does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-4} , then the risk is acceptable;

Step 3a_{III}¹: The summation of the values related to all the individual risks calculated in step 1a_{III}¹ to determine the group risk (R_{grup});

Step 4a_{III}¹: If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-3} , then the risk is acceptable.

b_{III}^1 . If the ES is procedurally independent of PES1, then the following procedural steps are followed:

Step 1 b_{III}^1 : The individual risks ($R_{individual}^{1,2}$) generated by PES1 and PES2 for each person in the ES are calculated;

Step 2 b_{III}^1 : If the maximum $R_{individual}^{1,2}$ calculated in step 1 b_{III}^1 does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-6} , then the risk is acceptable;

Step 3 b_{III}^1 : The summation of the values related to all the individual risks calculated in step 1 b_{III}^1 to determine the group risk (R_{grup});

Step 4 b_{III}^1 : If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-5} , then the risk is acceptable.

a_{III}^2 . If the ES is procedurally dependent on PES2, then the following procedural steps are followed:

PES2

Step 1 a_{III}^2 : The individual risks ($R_{individual}^{1,2}$) generated by PES1 and PES2 for each person in the ES are calculated;

Step 2 a_{III}^2 : If the maximum $R_{individual}^{1,2}$ calculated in step 1 a_{III}^2 does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-4} , then the risk is acceptable;

Step 3 a_{III}^2 : The summation of the values related to all the individual risks calculated in step 1 a_{III}^2 to determine the group risk (R_{grup});

Step 4 a_{III}^2 : If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-3} , then the risk is acceptable.

b_{III}^2 . If the ES is procedurally independent of PES2, then the following procedural steps are followed:

Step 1 b_{III}^2 : The individual risks ($R_{individual}^{1,2}$) generated by PES1 and PES2 for each person in the ES are calculated;

Step 2 b_{III}^2 : If the maximum $R_{individual}^{1,2}$ calculated in step 1 b_{III}^2 does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-6} , then the risk is acceptable;

Step 3 b_{III}^2 : The summation of the values related to all the individual risks calculated in step 1 b_{III}^2 to determine the group risk (R_{grup});

Step 4 b_{III}^2 : If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-5} , then the risk is acceptable.

For the safe placement of a PES type structure, the same work algorithm is applied, respecting the process reasoning.

IV. Scenario no. 4 of the arrangement of several explosive structures in relation to several exposure structures (PES1, PES2, ES1, ES2 and ES3)

In order to safely place several ES-type structures in the case shown in figure 5, each PES will be evaluated individually in relation to these (ES-type) structures following the following work process algorithm:

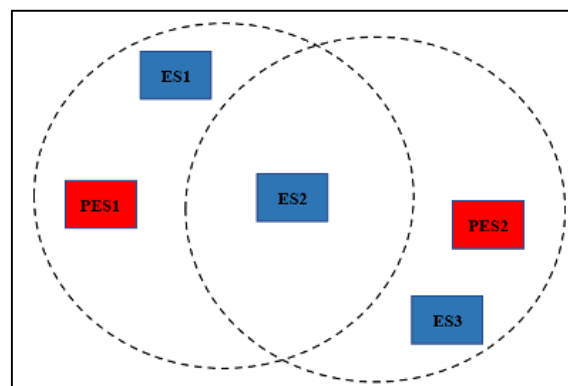


Figure 5. Risk-based layout of the five distinct structures (PES1, PES2, ES1, ES2 and ES3)

a_{IV}^1 . If ES1, ES2 and ES3 are procedurally dependent on PES1, then the following procedural steps are followed:

PES1

Step 1 a_{IV}^1 : Both the individual risk ($R_{individual}^1$) generated by PES1 for each person in ES1 and ES2 and the individual risk ($R_{individual}^2$) generated by PES2 for each person in ES2 and ES3 are calculated;

Step 2a_{IV}¹: If the maximum $R_{\text{individual}}^{1,2}$ calculated in step 1a_{IV}¹ does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-4} , then the risk is acceptable;

Step 3a_{IV}¹: The summation of the values related to all the individual risks calculated in step 1a_{IV}¹ to determine the group risk (R_{grup});

Step 4a_{IV}¹: If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-3} , then the risk is acceptable.

b_{III}¹. If ES1, ES2 and ES3 are procedurally independent of PES1, then the following procedural steps are followed:

Step 1b_{IV}¹: Both the individual risk ($R_{\text{individual}}^1$) generated by PES1 for each person in ES1 and ES2 and the individual risk ($R_{\text{individual}}^2$) generated by PES2 for each person in ES2 and ES3 are calculated;

Step 2b_{IV}¹: If the maximum $R_{\text{individual}}^{1,2}$ calculated in step 1b_{IV}¹ does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-6} , then the risk is acceptable;

Step 3b_{IV}¹: The summation of the values related to all the individual risks calculated in step 1b_{IV}¹ to determine the group risk (R_{grup});

Step 4b_{IV}¹: If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-5} , then the risk is acceptable.

a_{IV}². If ES1, ES2 and ES3 are procedurally dependent on PES1, then the following procedural steps are followed:

PES2

Step 1a_{IV}²: Both the individual risk ($R_{\text{individual}}^1$) generated by PES1 for each person in ES1 and ES2 and the individual risk ($R_{\text{individual}}^2$) generated by PES2 for each person in ES2 and ES3 are calculated;

Step 2a_{IV}²: If the maximum $R_{\text{individual}}^{1,2}$ calculated in step 1a_{IV}² does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-4} , then the risk is acceptable;

Step 3a_{IV}²: The summation of the values related to all the individual risks calculated in step 1a_{IV}² to determine the group risk (R_{grup});

Step 4a_{IV}²: If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-3} , then the risk is acceptable.

b_{IV}². If the ES is procedurally independent of PES2, then the following procedural steps are followed:

Step 1b_{IV}²: Both the individual risk ($R_{\text{individual}1}$) generated by PES1 for each person in ES1 and ES2 and the individual risk ($R_{\text{individual}2}$) generated by PES2 for each person in ES2 and ES3 are calculated ;

Step 2b_{IV}²: If the maximum $R_{\text{individual}}^{1,2}$ calculated in step 1b_{IV}² does not exceed the risk limitation/reduction criteria P_f (table 6) of 1×10^{-6} , then the risk is acceptable;

Step 3b_{IV}²: Însurarea valorilor aferente tuturor riscurilor individuale calculate la pasul 1b_{IV}¹ pentru determinarea riscului de grup (R_{grup});

Step 4b_{IV}²: If R_{grup} does not exceed the risk limitation/reduction criteria E_f (table 6) of 1×10^{-5} , then the risk is acceptable.

For the safe placement of several PES structures, the same work algorithm is applied, respecting the process reasoning.

3. Discussion and conclusion

In this paper, a methodology for quantitative assessment of explosion risk was presented, which is based on the specialized use of the concept of risk specific to industrial sites intended for operations with explosive materials.

In the field of risk analyzes associated with explosion-type events caused by specific operations with explosive materials, the logarithmic scale is usually used to estimate the result indicator, because: the range of values specific to the area of interest for carrying out the risk estimation can include several orders of size; lends itself very well to quantitative risk assessment; the principle of proportional logic is ensured, according to which multiplying the risk by a constant value leads to a constant separation (variation) of it.

The concept of risk assessment is a sequential process that involves both the quantitative assessment of risk based on available data and information (accident history and statistics, test and trial results, technical-scientific information, safety data sheets, technical product specifications, the experience and technical expertise in the field of the experts), as well as the qualitative evaluation regarding the risk assessment taking into account the subjective aspects and the perception of the way of manifestation and generation of specific effects.

The main mechanisms of damage through death or injuries (major or minor), as well as through material destruction, following the production of an explosion-type event when carrying out specific operations with explosive materials, which can be grouped as follows: *Overpressure and impulse* (overpressure from shock wave front); *Structural response* (destruction of buildings and shattering of windows with projecting resulting fragments); *Debris* (fragments resulting from the detonation of explosive materials, originating from: explosive products - primary fragments; construction materials of spaces intended for operations with explosive materials - secondary fragments; pieces of rock from formed craters - auxiliary debris); *Thermal radiation* (specific to explosives included in the division HD 1.3 - explosives that cause mass fires).

The risk analysis should be carried out in a way that recognizes the mechanism of compliance with the mathematical legitimacy of „adding” the risk values taking into account its nature. In this sense, the risk-based disposition of explosive structures (PES) and exposure structures (ES) within an industrial site intended for carrying out specific operations with explosive materials, is done by ensuring that all PES-type structures that expose a structure of ES type at a significant „individual risk – $R_{individual}$ ” are taken into account in the analysis and by evaluating the „group risk”.

For the complete definition of event scenarios within the framework of risk analyses, which are subject to the involvement of explosive materials, specific data and relevant information necessary for the full characterization of explosive structures (PES) and exposure structures (ES) must be used, respectively: size, shape, type and construction category, orientation, type of explosive, classification in the hazard class and compatibility group of the explosive, the net amount of explosive stored/used, the type of activity carried out at the level of the exposed structure, the number of people present and the annual exposure (in hours) at the level of the exposure structure.

In the case of the quantitative evaluation of the explosion risk generated following the detonation of explosive materials, the estimation of the manifestation of hazards identified through the associated risk factors, is carried out on the basis of established scientific calculation algorithms and grapho-analytical models, taking into account databases substantiated data from the results of experimental research regarding the characterization of the effects and consequences related to typical event scenarios with different exposures at predefined distances, in accordance with standard safety criteria, using the technique of extrapolating the effects of the far field to the area near the epicenter of the explosion (near field), while of course retaining the size of the proportion of the modeled effect, characteristic of the simplified fatality mechanism caused by an explosion-type event.

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